Reproduced by the
CLEARINGHOUSE

Best
Available
Copy

U.D.C. 629.19.066.5

ROYAL AIRCRAFT ESTABLISHMENT

Technical Report 69007

January 1969

LARGE SOLAR ARRAY DEVELOPMENT IN U.K.

by

F. C. Treble

SUMMARY

Aspects of large solar array technology are reviewed, with particular reference to the development of an experimental 560 W deployable array, which has some novel features.

The array consists of very thin silicon solar cells mounted on Kapton polyimide film. It is stowed by folding the Kapton concertina fashion into rectangular compartments and deployed by pneumatically-actuated telescopic masts. Deployment is initiated by duplicated pyrotechnic actuators and takes about two minutes to complete.

The estimated all-up weight of the 78 ft^2 array, including stowage compartments, cushioning and deployment mechanism is 25·2 lb, giving a power-weight ratio of 22·3 W/lb at 55°C.

The main problem areas are discussed in some detail, with an indication of the progress made to date.

Paper presented at the 7th IEEE Photovoltaic Specialists' Conference, Pasadena, U.S.A., 19-21 November 1968.

Departmental Reference: Space 291

CONTENTS

1 INTRODUCTION

British efforts in the field of large stowable solar arrays are directed towards the development of lightweight solar cells, assembly techniques and stowage and deployment systems to yield all-up array power-weight ratios in the region of 20 to 25 W/lb. Potentially, there are many scientific and commercial applications for such arrays, but U.K. is particularly interested in those which involve orbit expansion or other space manoeuvres by small electrically propelled spacecraft. This is a subject which King-Hele[1] and Burt[2,3] have explored theoretically in some depth.

Current work is centred on the development of an experimental deployable array for a 250 lb spacecraft, which could be used to demonstrate the feasibility of near-Earth orbit expansion by electric propulsion in the mid-1970's. It is hoped that the innovations and improvements in array technology which will be stimulated by this programme will find other space applications.

The proposed design, which has some novel and interesting features, is described in this paper. The main problem areas are then discussed in turn and an indication given of the progress made so far in the development and testing of the array hardware.

2 THE PROPOSED DESIGN

Fig.1 is an artist's impression of the proposed array, fully deployed.

The spacecraft carries a propane jet attitude control system and is equipped with an ion engine (not shown) which will have a thrust of 0.015 N and and exhaust velocity of 30 km sec^{-1}, requiring 500 W from the array. It is proposed to launch the spacecraft into a 'full sun' orbit at an inclination of 81° to the Equator. In this orbit, the solar paddles can be kept facing the Sun without having to rotate them relative to the spacecraft and the thrust vector can be kept along the orbital path by using signals from an earth sensor. If the launch is properly timed, about 20 days of continuous sunlight will be available, during which it is hoped to demonstrate orbit expansion. After this, the progressively increasing periods of darkness will provide an opportunity for checking the automatic shut-down and start-up sequences which it is planned to incorporate in the system.

Each of the solar paddles is 165 inches long × 36 inches wide and consists of two panels of thin silicon cells mounted on flexible plastic sheet and supported by a pneumatically-deployed telescopic mast. The total panel area is about 78 ft^2.

The mast is made of six 39 inch sections of thin-walled (0.015 inch to 0.020 inch) aluminium alloy tube. The outermost section is 1 3/8 inches in diameter and the innermost 2 inches. The diameters of mating tubes differ by 1/8 inch. Each tubular section carries on its outboard end a cross-member of aluminium honeycomb, to which the array is attached for support. Fig.2 shows the method of attachment. The piano-hinge joints at the cross-members divide each panel into sub-panels to facilitate repair and replacement.

The panels are stowed by folding them concertina-fashion in two aluminium honeycomb compartments, the cross-member on the outermost tube forming the cover of the compartment. The method of stowing is illustrated in Fig.3. The panel folds up into a stack 2.5 inches wide, the same width as the intermediate cross-members, and is interleaved with captive sheets of thin plastic. Cushioning pads are attached to the bottom of the compartment, the underside of the cover and both sides of the intermediate cross-members.

A cross-section of the compartment, through the stowed telescopic mast is shown in Fig.4. Weight is saved by using the central tube of the mast as the gas bottle for the deployment system. The tube is charged with dry nitrogen to a pressure of 2 to 3 atmospheres through a valve in the outboard extremity. A pyrotechnically-operated release mechanism detailed in Fig.5, connects the inner and outer tubes, maintaining the stowed array under a load of about 400 lb and restraining the nest of tubes against centrifugal and acceleration forces, which together amount to about 40 g.

The release mechanism operates when either of the two pyrotechnic actuators is fired. When this occurs the initial expansion of the stowed array, together with forces exerted by the pyrotechnics and the loading spring, pushes off a sleeve on the central spindle and uncovers a small port, which allows the compressed gas to pass at a controlled rate from the central tube to the release mechanism chamber and so initiate deployment. Seals on the outside of each tube impart a piston action, first to the central tube and then successively to the others, as each preceding tube is fully extended against a conical ptfe stop. Keys fixed externally along the length of each tube mate with ptfe pads in the bore of the adjacent section to prevent rotation during deployment. The pads and seals also serve to keep the tubes concentric. Simple pawls at the ends of the tubes engage in serrations to prevent return until manually operated.

During deployment, which takes about 2 minutes, the folded panels are drawn progressively from the stowage compartments, leaving the plastic interleaving sheets behind. A small bleed allows the pneumatic system to become fully depressurized after 30 minutes, the gas being released in such a way that it does not cause disturbing torques on the spacecraft.

This system of stowage and deployment was devised only after careful assessment of a number of alternatives, including roll-up arrays, folding rigid panels and inflatable, chemically-rigidized systems. Its main advantages lie in its lightness and simplicity and the fact that the solar cells are stowed flat and adequately supported under pressure during the launch and injection phases. The whole system can be repeatedly ground tested before launch.

The natural frequency of the paddle about the telescopic mast (torsional mode) has been estimated[4] at 6.4 c/s and about the spacecraft axis (flapping mode) at 2.5 c/s. In both modes vibrations would be well damped by virtue of the clearances between the parts of the assembly.

Electrically, the array is constructed of 14880 10 ohm cm n-on-p silicon cells, 2 cm square × 0.005 inch thick, individually covered with 0.004 inch cover slips. Fig.6 shows how they are arranged on each paddle.

Each of the small rectangles represents a patch of 20 cells in series × 3 in parallel, which, at an estimated maximum temperature of 55°C, produces 2.26 W at 7 V in normal sunlight above the atmosphere. The patches are series connected in modules to give the output voltages required for the ion engine and auxiliary power supplies. Positive and negative bus-bars paralleling the modules of each section, run side-by-side down the inner edges of the panels adjacent to the telescopic mast and terminate in connectors attached to the stowage compartments. Details are given in Table 1.

<u>Table 1 - Array details</u>

Load	Estimated output power (55°C) W	Output voltage V	Number of 20 × 3 cell patches on each side of the spacecraft		Number of series patches in a module
			Panel 1	Panel 2	
Ion engine	507	56	56	56	8
Auxiliary power	45	14	4	6	2
	9	7	2	0	1
Total:	561		62	62	

The folds in the stowed panels are arranged to come between the cell patches, which are pitched at 2.5 inch intervals. Thus, the bus-bars and series connections between patches are the only conductors which cross the folds.

The performance of the array will not be significantly affected by radiation encountered during the proposed mission, which is estimated to be equivalent to 5×10^{13} electrons cm^{-2} at 1 MeV. Indeed, for this particular mission, it would be advantageous to use 1 ohm cm cells, which are less radiation resistant than 10 ohm cm, but give a higher initial maximum power. However, 10 ohm cm were chosen with an eye to future missions, which may extend a year or more.

3 WEIGHT ESTIMATE

The breakdown in Table 2 shows the total estimated weight of the array to be 25.2 lb. The stowage compartments, cushioning and deployment mechanism account for 53% of the total.

The power-weight ratio, based on a total output of 560 W at 55°C, works out at 22.3 W/lb. At 30°C, it is 26.5 W/lb. These figures are based on currently attainable 10 ohm cm cell performance and take no account of radiation damage.

The power-area ratio is 7.2 W/ft^2. This is rather less than the current figure for conventional arrays, due to the poorer initial performance of thin silicon cells and the unused panel areas at the folds, at the cross-members and adjacent to the stowage compartment. The difference would be smaller in a design catering for radiation fluences equivalent to more than 10^{15} 1 MeV electrons cm^{-2}, because, after this flux, 0.005 inch cells perform as well as cells of conventional thickness[5].

4 THE SOLAR CELLS

Thin silicon solar cells have been under development in U.K. over the past two years and have now reached the stage of pilot production. They were chosen in preference to polycrystalline thin film cells because of their higher efficiency and more advanced technology. Experience so far has indicated that it should be possible to make consistently good silicon cells 0.004 inch to 0.006 inch thick in large numbers at a reasonable price. Despite the fragility of the cells, satisfactory production yields have been obtained.

Table 2 - Array weight breakdown

Component	Estimated weight for one paddle (lb)
1. Solar cells, silicon, 0.005 inch thick	2.11
2. Cover slips, glass, 0.004 inch thick	1.66
3. Cement, silicone rubber, 0.003 inch thick	0.55
4. Interconnections, Invar, 0.001 inch thick (including solder)	0.66
5. Bus-bars, copper (including solder)	0.33
6. Substrate, Kapton, 0.002 inch thick	0.57
Total for basic solar cell panel	5.88
7. Stowage compartment, alum. honeycomb	2.50
8. Cushioning pads, expanded polythene	0.12
9. Interleaves, 0.001 inch Kapton	0.28
10. Telescopic mast, aluminium tube	2.40
11. Cross-members, alum. honeycomb	0.90
12. Tube end fittings	0.10
13. Release mechanism	0.10
14. Interlocks (pawls etc.)	0.10
15. Seals, stop cones and keyway pads, ptfe	0.10
16. Miscellaneous	0.10
Total for stowage and deployment system	6.70
Grand Total (one paddle)	12.58
Total weight of array (two paddles)	25.16

Two types of contact, the Ferranti plated Ni-Cu-Au, as used on the Ariel 3 and ESRO 2 satellites, and the evaporated Ti-Ag have been assessed in two configurations - the conventional arrangement with the negative contact on the front and the 'wrap-round' type, with both contacts on the back. Also, 1 ohm cm and 10 ohm cm versions have been compared. Fuller details of this assessment are presented in another paper[6] at this Conference.

Fig.7 shows the performance spreads of three different types of uncovered wrap-round cells. The loss on covering is negligible.

5 PANEL SUBSTRATE

The most important properties required of the substrate are:-

(a) High tensile strength-weight ratio and high modulus of elasticity.

(b) Resistant to tearing, particularly when perforated.

(c) Resistant to UV and corpuscular radiation.

(d) Easy to fold and capable of withstanding repeated folding and unfolding during stowage and deployment tests.

(e) Able to withstand soft soldering temperatures.

(f) Flexible at low temperatures and resistant to thermal cycling in orbit.

(g) Resistant to long periods of high vacuum.

(h) Commercially available in large flat sheets.

Kapton polyimide film appears to be the best available material for the purpose, as it meets all the above requirements and has an exceptionally wide temperature range (+400°C to -269°C). The thickness being used in current development is 0.002 inch.

6 CELL INTERCONNECTION AND MOUNTING

The main problem in this area is to devise a light method of interconnecting the cells and attaching them to the substrate which will stand up to the severe thermal cycling experienced by exposed spacecraft structures of low thermal capacity as they move into and out of the Earth's shadow. It has been calculated, for instance, that the temperature of the thin paddles of a satellite in the geostationary orbit would fall from a maximum of 55°C in sunlight to about -180°C at the end of the period of eclipse. In lower orbits, the minimum temperatures would be higher than this, owing to the shorter time spent in eclipse and the greater influence of heat radiated from the Earth. Pending an accurate assessment, the minimum array temperature in the proposed mission has been assumed to be -120°C.

From the data in Table 3, it is evident that serious thermal mismatch can occur in a solar array, which may lead to failure when it is repeatedly heated and cooled over such extensive temperature ranges. Mismatch at the cell contacts can be reduced by keeping the area of soldered joints as small as possible and making the interconnections of Invar instead of copper or silver,

although the use of this material may be open to objection when extreme magnetic cleanliness is required. Also, it is a good rule to avoid encapsulating the interconnections in mounting cement or, better still, to dispense with cement wherever possible.

Table 3 - Coefficients of linear expansion

Material	Coefficient of expansion $\times 10^{-6}/^{\circ}C$
Glass	7
Silicone cements	152 to 187
Epoxy cements	56 to 83
Silicon	2.6
Printed circuit board	12.5
Copper	16.7
Silver	19
Invar (36% Ni, 64% Fe)	2
Solder	25
Kapton	20

Fig.8 illustrates some of the designs which are being assessed by thermal cycling in the present phase of development.

In design A, cells with conventional negative bar contacts are connected in series/parallel by Invar foil strips and the assembly is stuck to the Kapton sheet with a silicone cement.

In design B, the cells are individually bonded to the Kapton by localised patches of cement and the series and parallel connections are made separately by Invar foil strips, which are soldered to the back of the cells through small holes in the Kapton. (This is referred to hereafter as the 'solder-through' technique.) The series strips are fed through another set of perforations and soldered to the front contacts of the adjacent row of cells. The mounting cement does not encapsulate the interconnections.

Design C is a similar construction, except that the mounting cement is eliminated and replaced by a window in the Kapton behind each cell.

Design D again embodies the solder-through technique, with windows in the Kapton, but the cells have 'wrap-round' contacts. Fig.9 is a back view of

a test sample showing the windows and interconnections. The latter are designed to nest when the panel is folded as in the complete array.

The advantages of having both negative and positive contacts on the back of the cell are that it simplifies interconnection, improves the packing factor, enables the cells to be covered (and thereby rendered less fragile) before assembly, lends itself to printed circuit techniques and facilitates removal and replacement of damaged cells in the finished array.

The test sample is thermally cycled by repeatedly moving it from an electrically-heated enclosure to a liquid-nitrogen-cooled enclosure in vacuum, the movement being automatically controlled from a thermocouple mounted on the front of a cell. Fig.10 shows a typical cycle. The maximum rate of change of temperature, about 100°C/min, occurs when the sample first enters the hot enclosure. Data from some recent tests on designs A and C are presented in Table 4. Further work will be necessary to prove the consistency and reliability of the solder-through technique, but results so far indicate that this is a feasible method, at least for temperatures down to -120°C.

Table 4 - Thermal cycling data

Design	Description	Test details		Result
		No. of cycles	Temperature range	
A	Conventional contacts. Cement mounting. No cover slips.	100	+80°C to -130°C	Failed during test due to some cells breaking right across and front connecting tabs with silicon chips attached pulling away from cells.
C	Conventional contacts. Solder-through technique with windows in Kapton. (Series connections only.) No cover slips.	160 1370	+80°C to -95°C followed by +80°C to -120°C	No contact failures and no significant degradation in performance on completion of test.

Another aspect of cell mounting techniques which is being studied is their effect on the maximum temperature a sun-orientated array would attain in orbit. Comparative heat balance tests in a vacuum chamber have shown that a solder-through array with windows in the Kapton and an emissive coating on the

backs of the cells (design C or D) would run about 4°C hotter than a cement-mounted array (design A). A performance penalty of just over 2% would result, but as the mounting cement would increase the total array weight by more than this percentage, the power-weight ratio would not be adversely affected. Without windows or mounting cement, the array would reach a temperature up to 35°C higher than a cemented assembly. Some reduction can be achieved by increasing the area of the soldered joints and using large interconnections as radiators, but this spoils the thermal cycling capability and increases the weight.

Radiation damage aspects are also being investigated. In any particular space environment, Kapton-backed cells will be subjected to roughly twice the fluence experienced by conventional honeycomb-backed cells and in consequence will suffer 4% to 5% more power degradation after the knee of the damage curve has been reached. Before the knee, which, with 0.005 inch cells, occurs at 5×10^{14} 1 MeV electrons/cm^2, the difference will be less.

Low energy protons can be a particular hazard to unprotected contacts and cell surfaces, but tests[6] have shown that no trouble need be expected from this source, even with exposed back contacts as in designs C and D, if the Ferranti plated type are used. The thinner evaporated back contacts can be adequately protected from low energy protons by Kapton, cement or a thermal control coating. Where the front surface of the cell is not completely protected by the cover slip, it is necessary to coat the exposed surfaces with cement or solder.

It is planned to flight test sample patches of thin silicon cells embodying the most satisfactory mounting techniques on the Black Arrow X3 spacecraft.

7 PANEL ASSEMBLY

Considerable thought has been given to the problem of devising a cheap production process for assembling flexible array panels. Fig.11 illustrates a jig which is being developed for the purpose, using the method of mounting described as design D in the previous section.

The Kapton sheet, with piano-hinge joints and windows already formed in it, is supported on two rollers, between which there is a traversing head carrying a multiple punch. The first operation is to punch holes at accurate intervals across the width of the sheet to produce the pattern required for

one cell patch. Then the sheet is rolled forward in 2.5 inch steps and the operation repeated at each step. At present, the head is positioned manually by pointer and scale but an easier method will be substituted when the panel design is frozen.

Next, the punch is removed and a vacuum jig holding a complete patch set of covered cells, active face downwards, is slid beneath the Kapton and lined up with the first set of perforations. The interconnections are then soldered to the backs of the cells through the holes. Currently, this is being done by hand soldering with a small iron, but it is planned eventually to use a hot gas soldering fixture mounted on the traversing head. Trials have demonstrated that consistently reliable soldered joints, with an area accurately defined by the holes in the Kapton, can be produced in this way.

After all the patches have been assembled on the sheet, the bus-bars and inter-patch connections are added. In the early models, the bus-bars are being formed from copper foil or braid strips attached to the Kapton in the same way as is used for the cells, but printed circuit techniques will be considered later on.

The assembled panel is then ready to be transferred to another set of rollers for acceptance testing, before being attached to the supporting structure.

8 STOWAGE AND DEPLOYMENT SYSTEM

A full-scale mock-up of the stowage compartment and telescopic mast, with panels of dummy wrap-round cells, has been constructed to settle certain design details and establish a satisfactory stowage procedure.

One problem has been to devise a method of holding the plastic interleaving sheets captive without making stowage too difficult. The present solution is to 'file' them loose-leaf fashion on thin rods which extend upwards from the base of the stowage compartment. The deployed panel is supported vertically over the compartment and, as each fold is formed, an interleaving sheet is threaded on the rods before proceeding to the next fold. The sides of the compartment are removed during stowage, so that the stack may be easily inspected for folding faults as the operation proceeds. With folding completed, the sides are replaced and retaining caps are fitted to the tops of the interleaf rods. As the cover of the stowage compartment is pressed down, the rods slide through holes in the base, where they are finally secured by set screws.

Development of the telescopic mast, seals, release devise and retaining pawls is proceeding satisfactorily and so far has presented no serious problem.

Following the mock-up stage, it is planned to build a prototype paddle embodying, initially, glass-covered dummy cells and, later, patches of live cells for vibration and acceleration tests in the stowed condition, repeated deployment and re-stowing and mechanical tests in the fully deployed state. The deployment tests will be carried out vertically to minimize gravitational effects and facilitate panel stowage.

Acknowledgments

The author is indebted to his colleagues R.L. Crabb and A.A. Dollery for experimental data and to N.S. Reed, B.W. Jacobs and D. Gibson, who are responsible for the mechanical aspects of array development.

REFERENCES

No.	Author	Title, etc.
1	D.G. King-Hele	The enlargement of elliptic satellite orbits by continuous micro-thrust. Proc. 14th Int. Astronautic Cong. Paris 1963, Vol. IV, pp 155-171 (Springer Verlag Berlin, 1965)
2	E.G.C. Burt	On space manoeuvres with continuous thrust. Planet. Space Sci, Vol.15, pp 103-122, 1967
3	E.G.C. Burt	Space science and electrical propulsion. Discussion meeting on space science and technology. Royal Society, London, 27 February 1968
4	D. Gibson	Private communication, September 1968
5	R.L. Crabb F.C. Treble	Thin silicon solar cells for large flexible arrays. Space Research and Engineering No.11-12, Vol.3, 1967
6	R.L. Crabb D. Basnett	Environmental Assessment of British 4 mil silicon solar cells from pilot production. 7th IEEE Photovoltaic Spec. Conf. Pasadena, November 1968

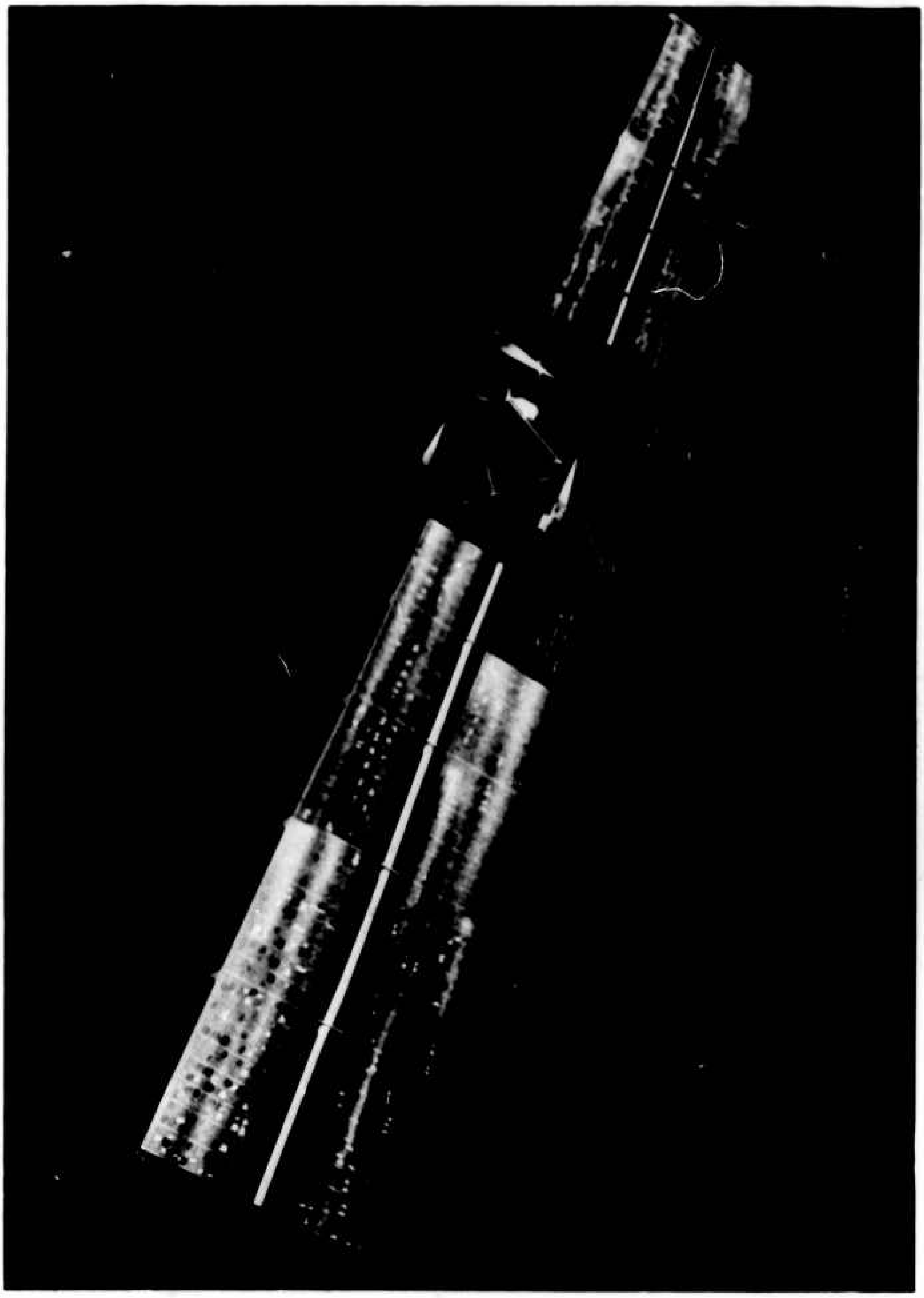


Fig.1. The proposed array

NEG.NO.C5591

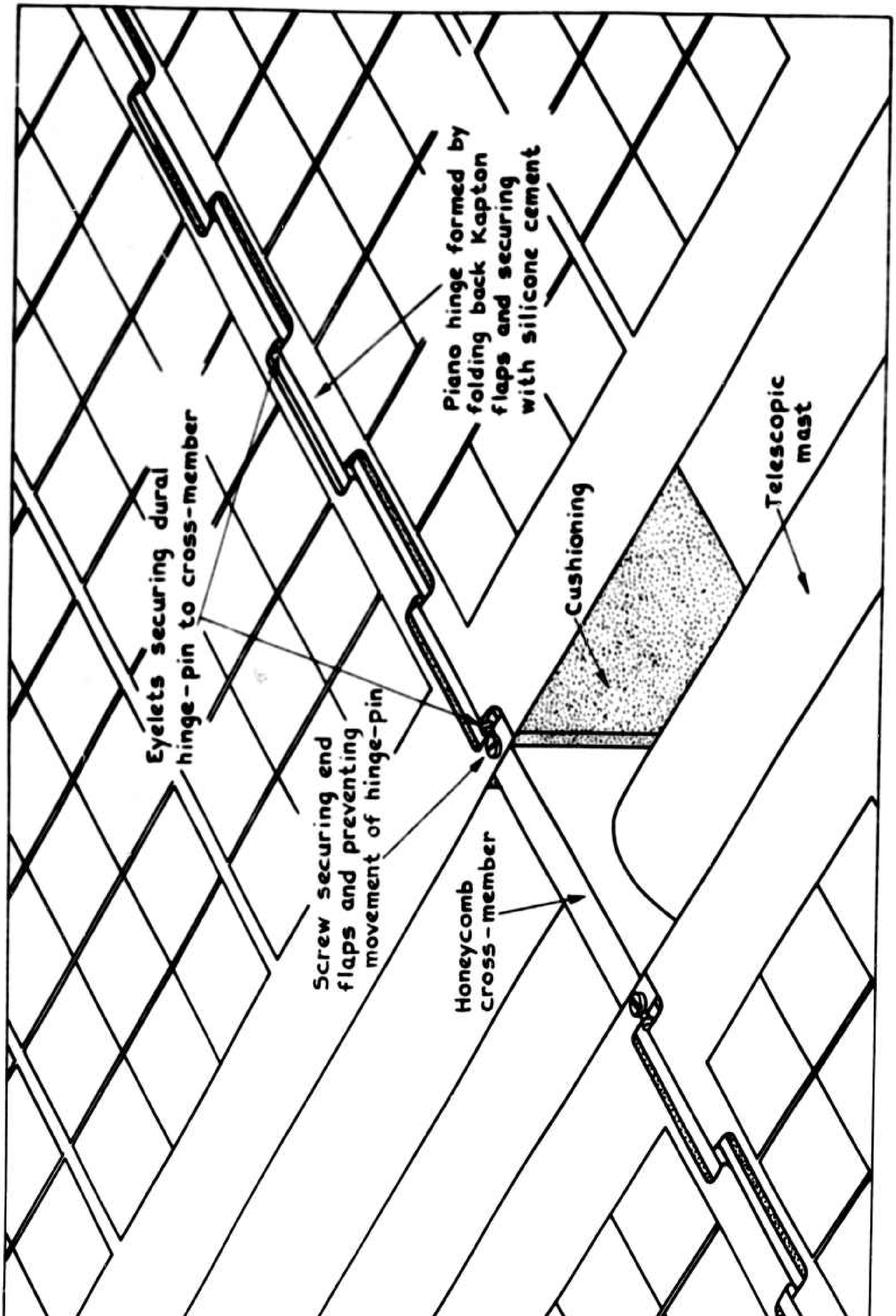


Fig. 2 Method of connecting sub-panels

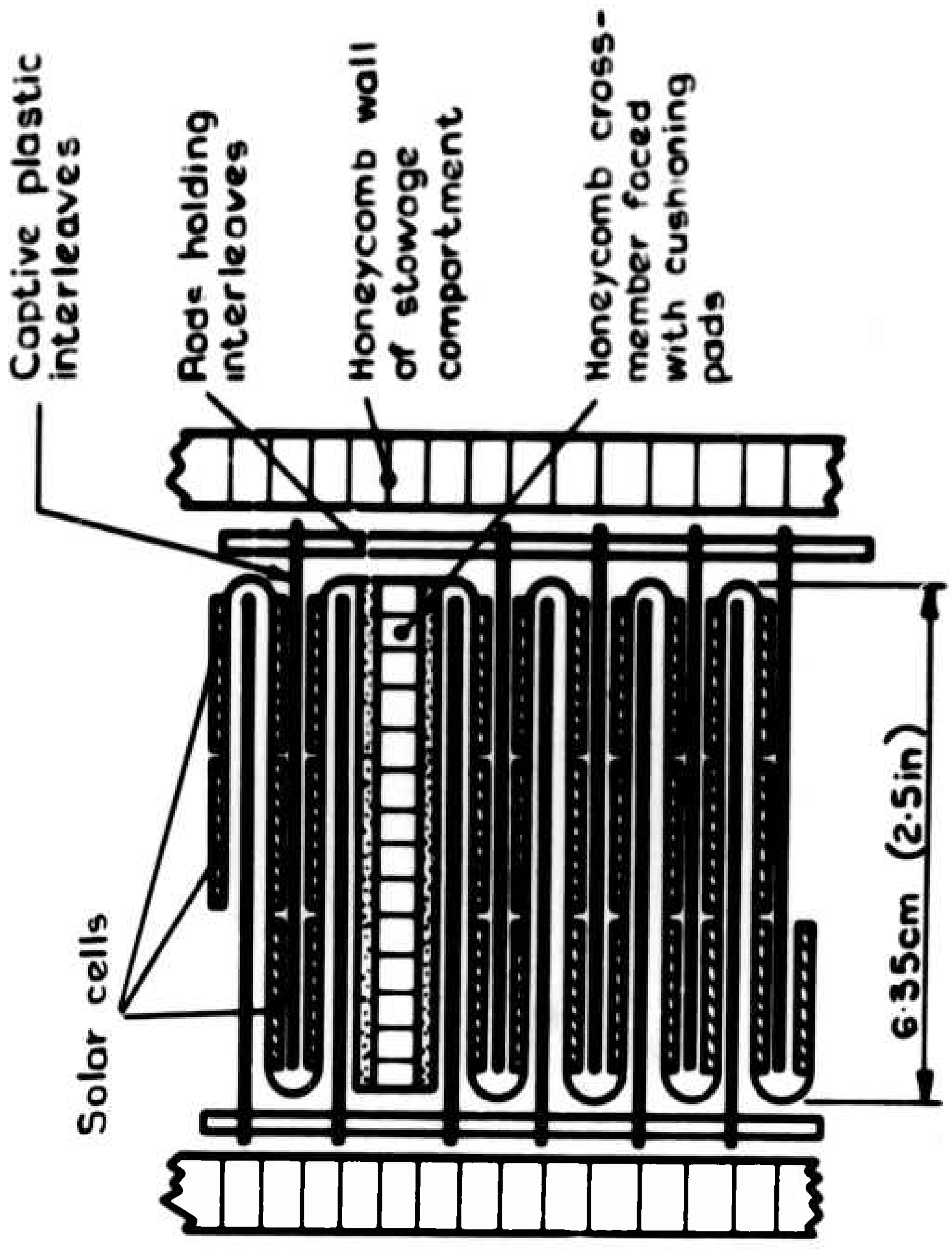


Fig. 3 Method of stowage

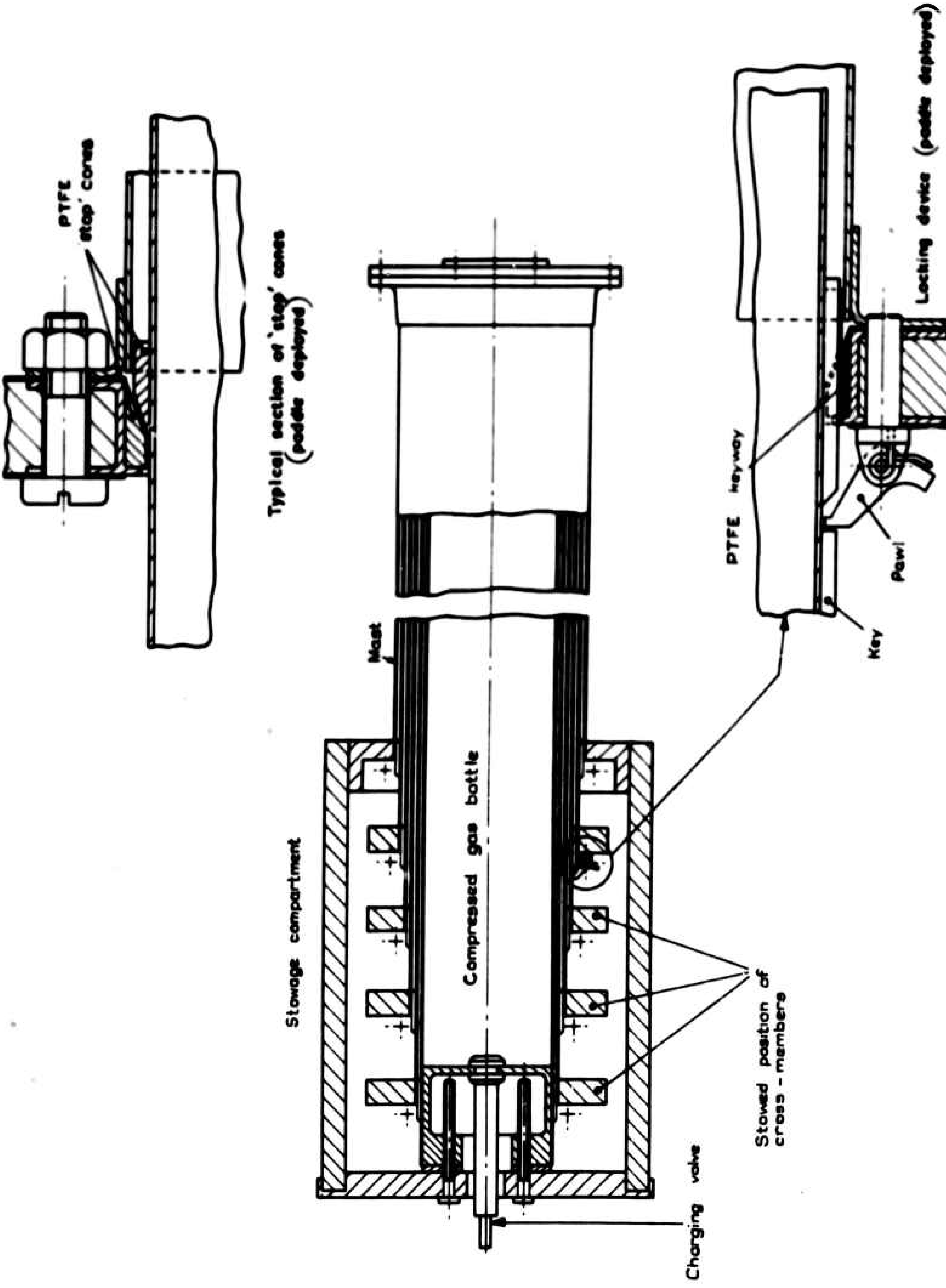


Fig 4 Stowage compartment & telescopic mast

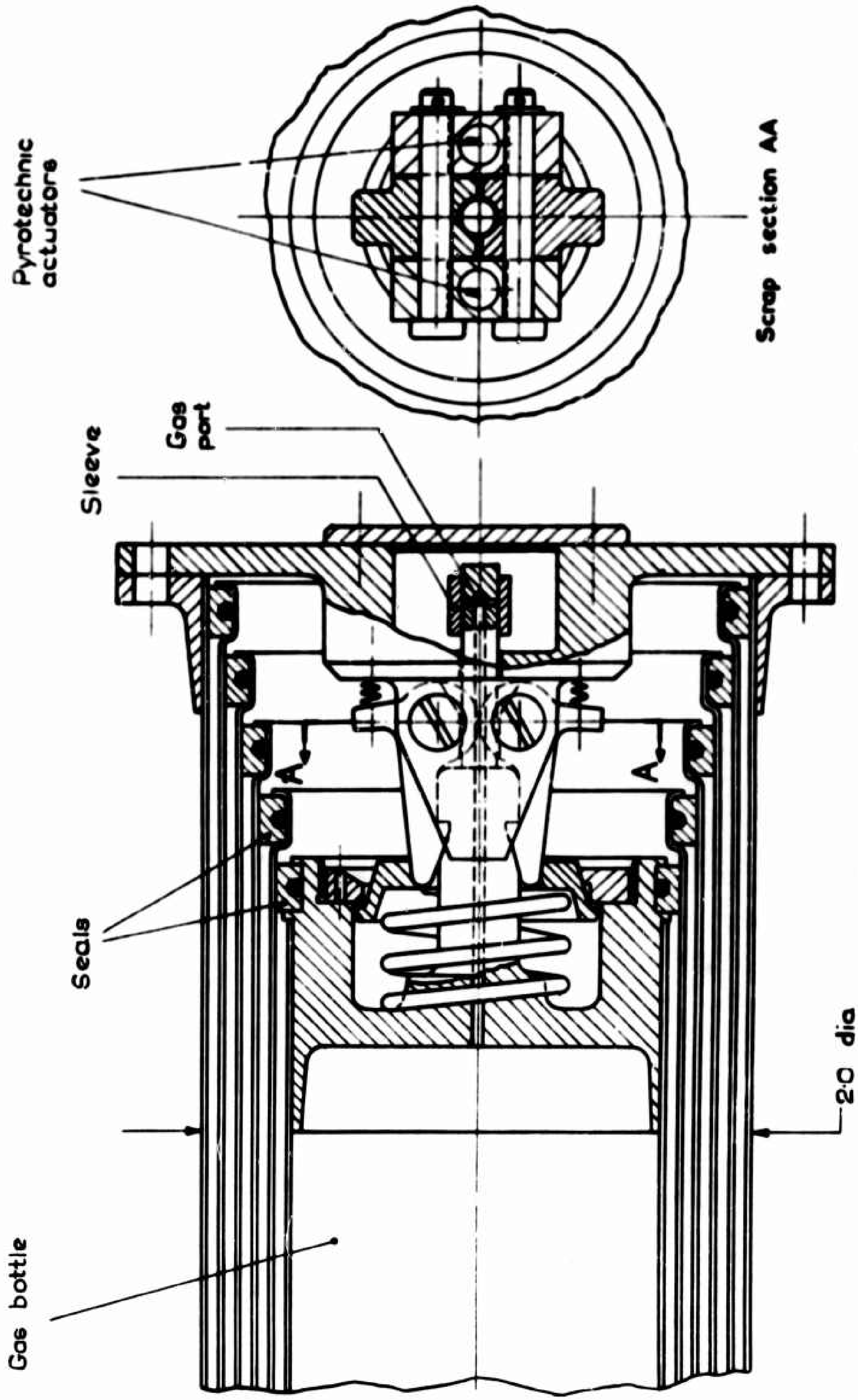


Fig.5 Release mechanism

Fig. 6

004 901674

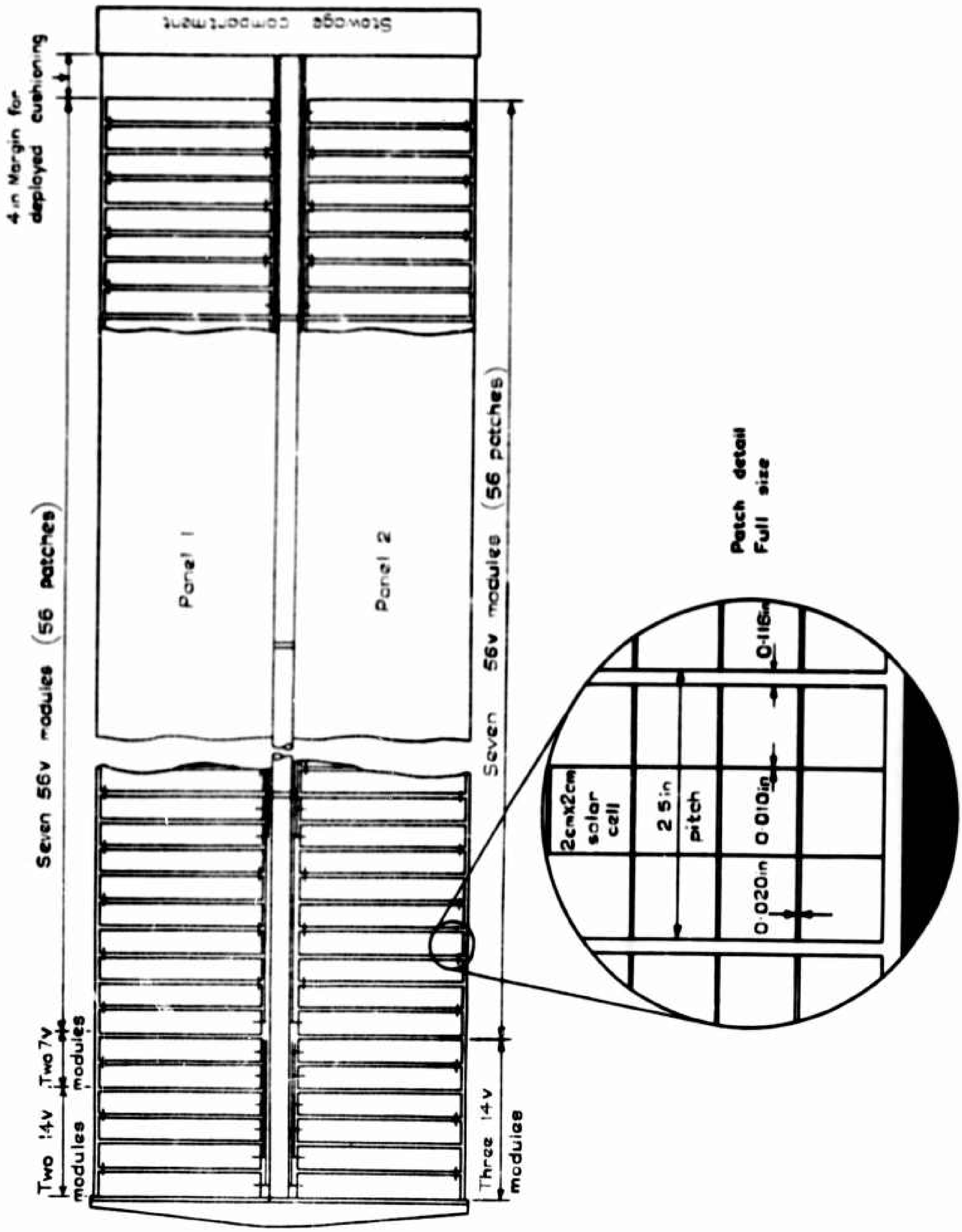


Fig. 6 Solar cell layout

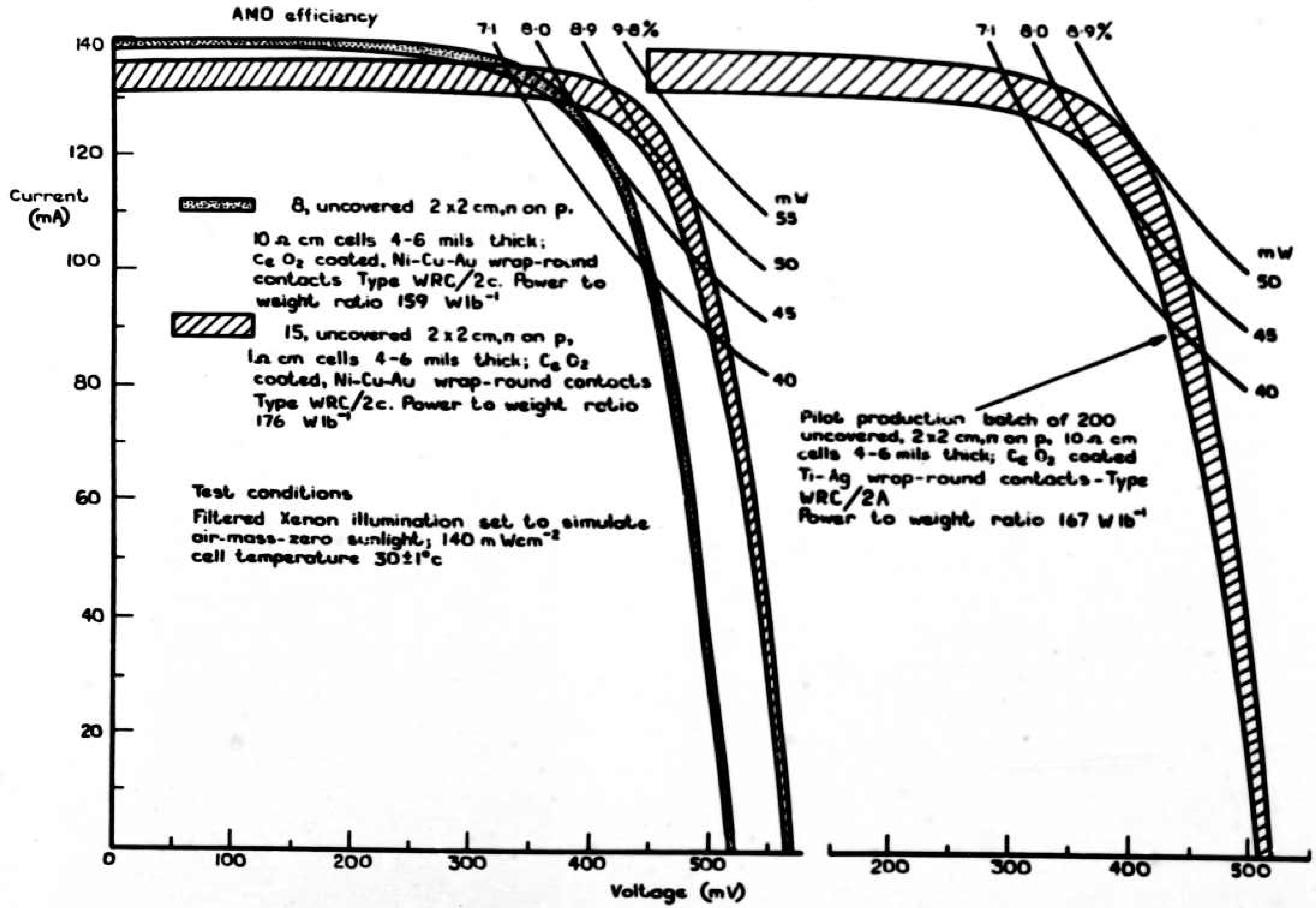
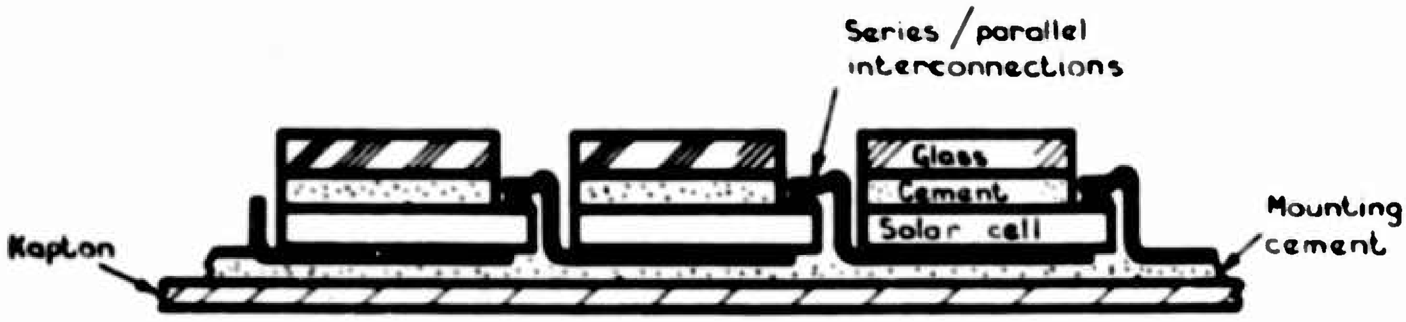
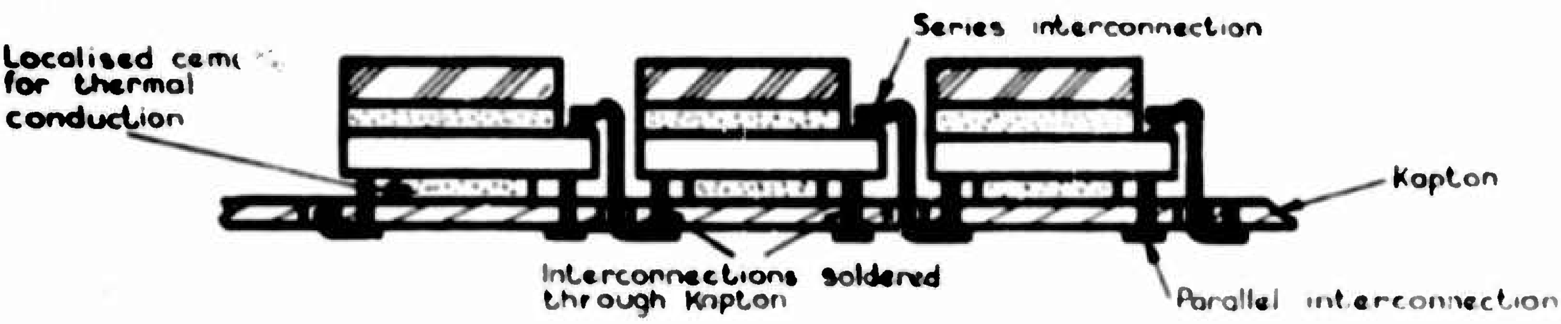


Fig.7 Performance spreads of thin silicon 'wrap-round' cells

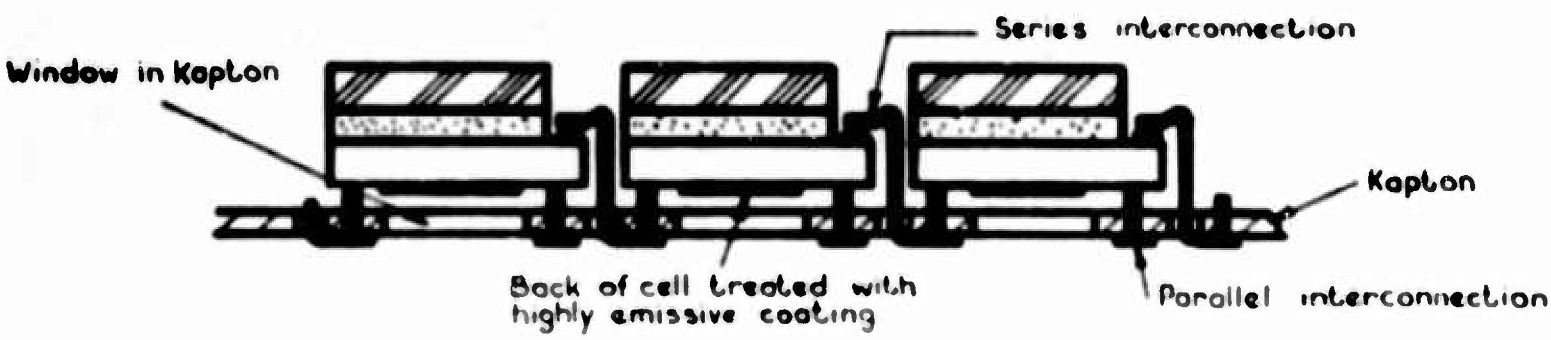
Fig. 8



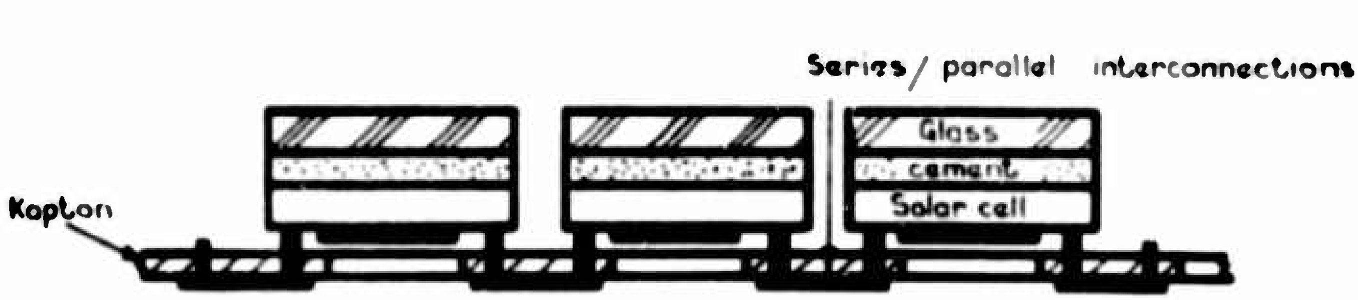
A Conventional contacts. Cement mounting



B Conventional contacts. Solder-through technique with localised mounting cement



C Conventional contacts. Solder-through technique with windows in Kapton



D Wrap-round contacts. Solder-through technique with windows in Kapton

Fig.8 Cell interconnections & mounting techniques

Fig. 9

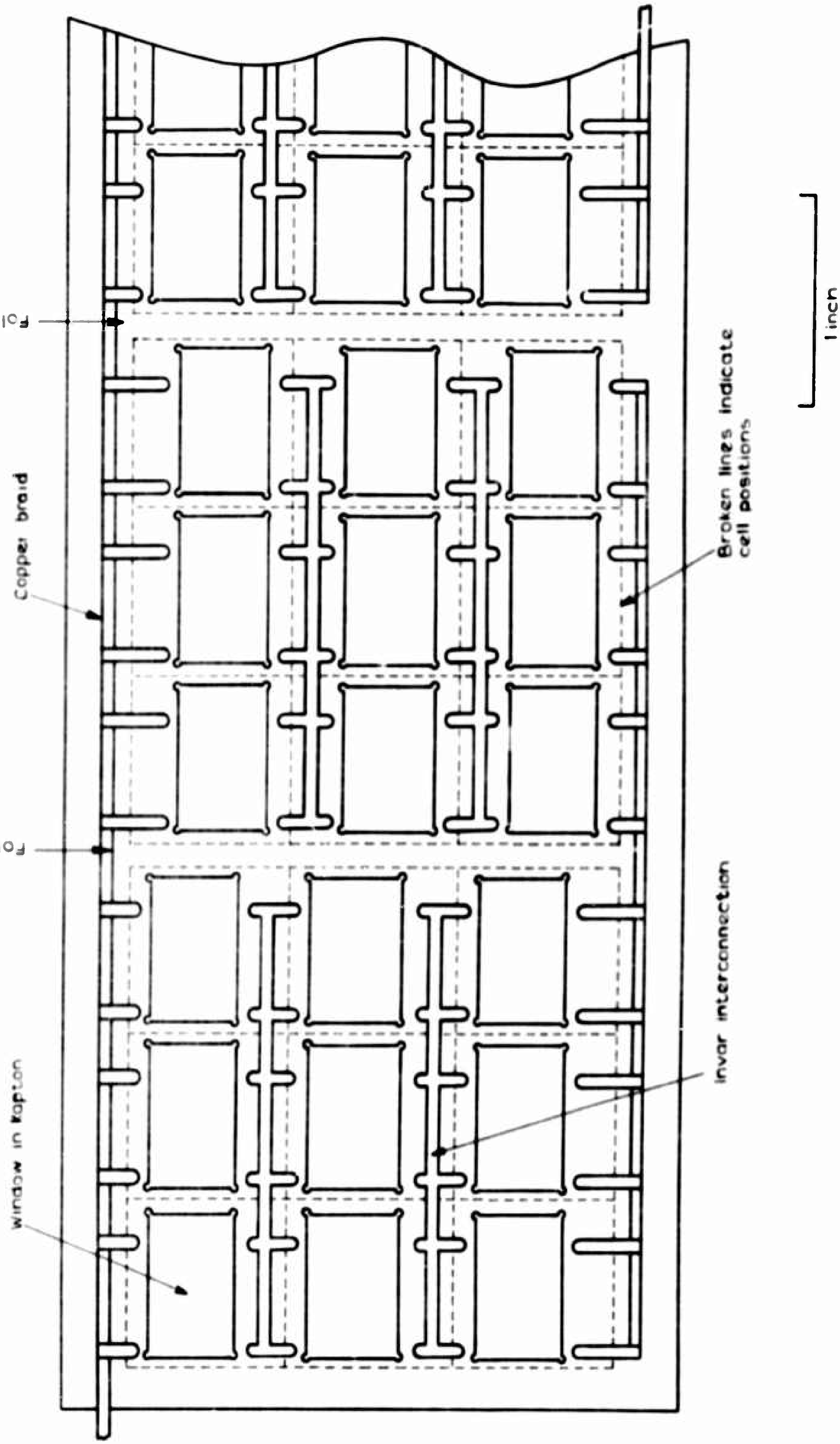


Fig 9 Back view of experimental panel of wrap-round cells

Fig. 10

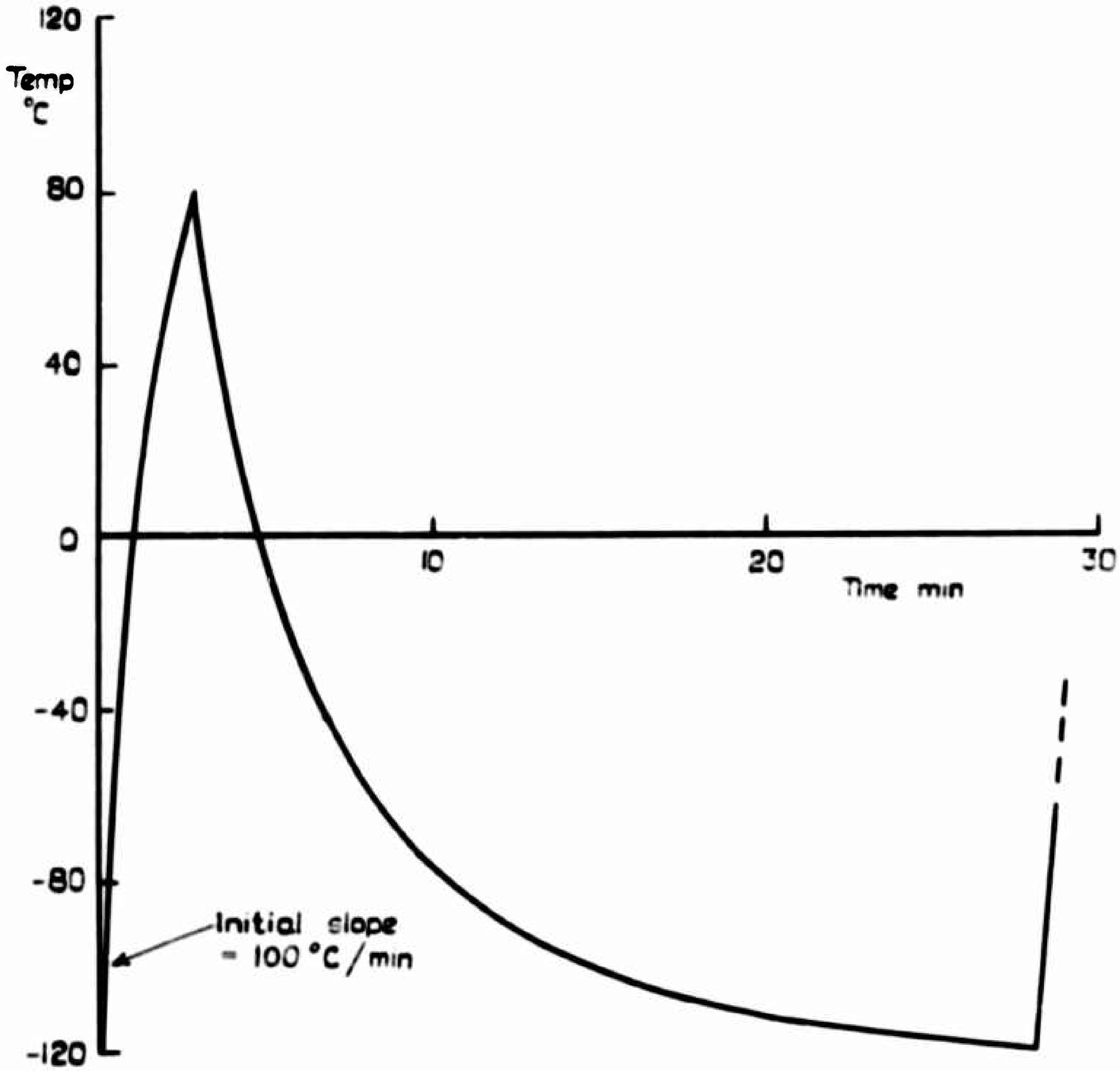


Fig. 10 Thermal cycle

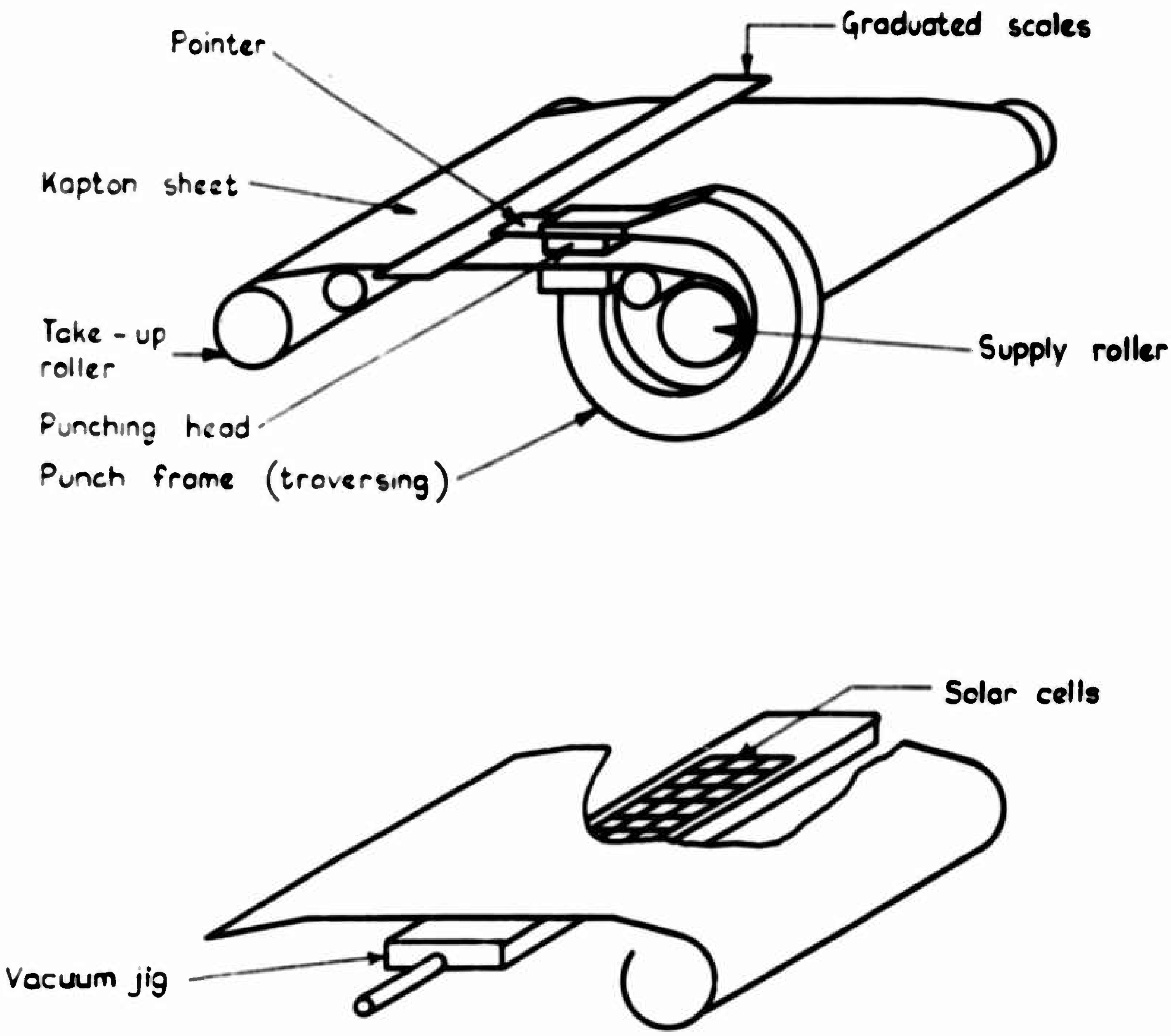


Fig. 11 Panel assembly unit